

Airborne Transmission of Virus-Laden Aerosols inside a Music Classroom: Effects of Portable Purifiers and Aerosol Injection Rates

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Abstract

The ongoing COVID-19 pandemic has shifted attention to the airborne transmission of small exhaled droplet nuclei within indoor environments such as classrooms. The spread of aerosols through singing and musical instruments in music performances has necessitated the need for utilizing precautionary methods such as masks and portable purifiers. This study investigates the effects of placing portable air purifiers at different locations inside a classroom, as well as the effects of different aerosol injection rates (e.g., with and without masks, different musical instruments etc.). The time varying deposition of aerosols on the walls and the airborne aerosol concentration are analyzed in this study. It was found that proper placement of purifiers could offer a significant advantage in reducing airborne aerosol numbers (offering orders of magnitude higher aerosol removal when compared to having no purifiers, where the removal is sometimes nearly zero), while improper placement of the purifiers could worsen the situation. It was concluded that in general, the purifier should be placed as close to the injector as possible in order to yield a benefit, and also away from the people to be protected. Moreover, using purifiers could help in achieving ventilation rates close to the prescribed values by WHO, while also achieving aerosol removal times within the CDC recommended guidelines. This could help in deciding effective break periods between classroom sessions, which was found to be around 25 minutes through this study. The injection rate was found to have an almost linear correlation with the average airborne aerosol suspension rate and aerosol surface deposition rate, which could be used to predict the trends for scenarios with other injection rates.

Keywords: COVID-19; airborne aerosol transmission; ventilation; portable purifier; musical instruments; computational fluid dynamics (CFD)

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1. Introduction

The transmission of the SARS-CoV-2 virus via small, exhaled airborne aerosols ($< 5 \mu\text{m}$) has been recognized as an important pathway for the spread of COVID-19 (Asadi et al., 2020; Prather et al., 2020; Jayaweera et al., 2020; Scheuch, 2020; Liu et al., 2020). Smaller aerosols suspended in the air (generally termed as “droplet nuclei”) are the crystalline, virus containing, non-volatile residue left behind once the liquid in the droplet evaporates out (Morawska, 2005; Johnson and Morawska, 2009; Shao et al., 2020). These smaller aerosols could actually carry more viral load than the larger droplets, since they originate from deep within the respiratory tracts where there is more viral concentration (Santarpia et al., 2020; Zou et al., 2020).

There have been several numerical studies investigating the spread and deposition of viral droplets and aerosols in enclosed spaces (Liu et al., 2020; Chao and Wan, 2006; Chao et al., 2008; Wan et al., 2009; Sze To et al., 2008; Sun and Ji, 2007; Gao and Niu, 2007; Zhu et al., 2006; Mui et al., 2009; Feng et al., 2020). All these studies support the fact that ventilation and modes of injection are important factors for the transport of airborne droplets and aerosols. Some recent studies have also attempted to perform a risk assessment in different indoor settings by studying the aerosol transport and deposition (Shao et al., 2020; Sze To et al., 2008; Morawska et al., 2013). In classroom/healthcare settings, a high ventilation rate is required to effectively remove the airborne virus-laden aerosols from the domain. A ventilation rate of least $288 \text{ m}^3/\text{h}$ per person is recommended by the World Health Organization (WHO) (Chartier and Pessoa-Silva, 2009). Such a ventilation rate might not be possible to achieve through natural ventilation alone, and sometimes even in-built ventilation systems may fall short of this target. In such cases, portable purifiers might help in increasing the net ventilation rate to achieve the desired level, which needs further investigation.

Portable High Efficiency Particulate Air (HEPA) purifiers have been used for indoor purifying requirements for relatively smaller domains such as classrooms, offices and hospital wards. A few studies have studied the efficacy of air purifiers for controlling the spread of COVID-19 (Christopherson et al., 2020; Zhao et al., 2020; Mousavi et al., 2020) and have concluded that such purifiers may serve as supplemental means for decontamination of SARS-CoV-2 aerosols. There have also been cases where portable purifiers increased the spreading of exhaled aerosols and therefore, worsened the situation (Ham, 2020). Currently, there are no formal recommendations by the Center of Disease Control (CDC) nor WHO for the usage of air purifiers. Therefore, the optimal use of air purifiers in an indoor setting remains a challenge to be studied.

Spreading of the SARS-CoV-2 aerosols via wind instruments and singing cannot be ignored, as observed in a COVID-19 outbreak among a choir rehearsal group (Read, 2020). The group had followed social distancing and regulations, and yet there were 45 cases out of which two succumbed to the disease. There have been studies pertaining to the spread of coronavirus through aerosols ejected from wind instruments, although most of them focused on the airflow from the instruments (Kähler and Hain, 2020; Becher et al., 2020; Spahn and Richter, 2020). A recent study examined the aerosol generation from different wind instruments and quantified the risk for each instrument (He et al., 2020). Singing can also be a dangerous source of virus-laden aerosols, having an injection rate typically greater than normal breathing and speaking (Salomoni

et al., 2016; Sommerstein et al., 2020; Alsved et al., 2020). Both singing and wind instrument playing can take place in a music classroom, prompting the need for careful consideration of the safety regulations and protocols inside these classrooms.

This study examines the effects of portable air purifiers inside the room, which are placed at different locations to determine the most strategic placement. Moreover, this study also examines different injection modes (such as using musical instruments, singing and normal breathing) with different injection rates for each mode (e.g., with and without masks, different instruments). The airborne aerosol concentration at the elevations of interest, the deposition of aerosols onto the surfaces inside the domain, and the amount of aerosols filtered by the purifiers are some key findings which will be reported in this study.

Section 2 specifies the governing equations considered in this study, followed by the model parameters and geometry of the domain. The results of the simulation are presented in Sec. 3, which examines the airborne aerosol concentration, airflow streamlines and wall deposition at various locations in the classroom under the different settings, as well as the number of aerosols remaining in the domain and vented/filtered out. The final section (i.e., Sec. 4) summarizes the study and draws important conclusions on which types of injection modes are the most risky in terms of prevailing airborne aerosol concentration, which purifier location is the most optimal in filtering out aerosols, and which spots in the room are riskiest in terms of the presence of airborne aerosols. This section also compares the improvement in ventilation due to the addition of purifiers, by comparing to the CDC and WHO suggested guidelines for ventilation rates.

2. Numerical Modeling

2.1. Computational fluid dynamics (CFD) simulation framework

The simulations are conducted based on the CONVERGE CFD platform version 2.4 (Richards et al., 2017). The Eulerian-Lagrangian framework is used for the gas-aerosol simulation. CONVERGE uses a nearest node approach to exchange mass, momentum, energy terms of a parcel (Lagrangian particle) with the fluid-phase (Eulerian field) values of the computational node that it is closest to. A Taylor series expansion is used to calculate the gas velocity (Eulerian field) at the point of the parcel (Lagrangian particle). The use of the Taylor series expansion significantly reduces grid effects on the spray. A collocated finite volume approach is used to numerically solve the conservation equations. Flow quantities are calculated and stored at cell centers according to the summed fluxes through the cell faces and an internal source term, if any. The gas phase flow is governed by the conservation equations of mass and momentum. The incompressible form of the equations are given below (since the Mach number is very low and the gas density is close to constant):

$$\rho \frac{\partial u_i}{\partial x_i} = S \quad (1)$$

$$\rho \frac{\partial u_i}{\partial t} + \rho \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_j} + \rho g_i + S_F \quad (2)$$

where σ_{ij} is the viscous stress tensor given by:

$$\sigma_{ij} = \mu \left(\rho \frac{\partial u_i}{\partial x_j} + \rho \frac{\partial u_j}{\partial x_i} \right) + \left(\mu' - \frac{2}{3}\mu \right) \left(\rho \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) \quad (3)$$

where t is time, g_i and u_i are the gravitational acceleration and velocity component in the i -th direction, respectively, ρ is the density of the gas, P is the pressure, μ is the viscosity, μ' is the dilatational viscosity (set to zero) and δ_{ij} is the Kronecker delta function. S and S_F are the source terms incurred by the Lagrangian particles, which are calculated by:

$$S = \frac{1}{V_{cell}} \left(\sum_i \dot{m}_i \right) = 0 \quad (4)$$

$$S_F = \frac{1}{-V_{cell}} \left(\sum_i \mathbf{F}_{i,drag} \right) \quad (5)$$

where the summation over i means the summation over all the Lagrangian particles within a cell, \dot{m}_i is the rate of change in mass of a particular Lagrangian particle (which is zero since break-up is neglected, and evaporation is assumed to have already reduced the particles to the minimum size: see more details below) and $\mathbf{F}_{i,drag}$ is the drag force on the Lagrangian particles. Evaporation is turned off for the duration of the simulation, since it was assumed that all the droplets ejected from the musical instruments (which are already $< 5 \mu\text{m}$ in size, as stated in He et al. (2020)) quickly evaporate to the minimum size (chosen to be $1.5 \mu\text{m}$ in this study), as justified in Shao et al. (2020). Aerosols around 1.5 microns are essentially the crystalline, non-volatile components leftover when the liquid in the droplet evaporates out. The assumption that the small droplets quickly evaporate into droplet nuclei within an order of few seconds is justified in past studies (Morawska, 2005; Stadnytskyi et al., 2020; Shao et al., 2020). The dispersed Lagrangian particles are modeled as spherical, $1.5 \mu\text{m}$ particles with a density equal to that of air at 300 K ($\rho = 1.161 \text{ kg/s}$). This assumption is validated by the fact that droplet nuclei leftover from fast evaporation possess very little inertia and hence follow the airflow (Morawska, 2005). This assumption is also similar to the “massless” particle assumption made by a recent study (Vuorinen et al., 2020), where the authors found that gravity and inertia play little role on particles $< 10 \mu\text{m}$. In addition, the ejected aerosols are pretty dilute (around 500 - 2000 particles per liter of ejected airflow) based on experimental observations (Shao et al., 2020; He et al., 2020) and hence, the interactions between Lagrangian particles are also ignored. The mass rate of change $\dot{m}_{i,d}$ and the total force (acting on the particle) $\mathbf{F}_{i,d}$ govern the dynamics of each Lagrangian particle by:

$$\frac{dm_i}{dt} = \dot{m}_i \quad (6)$$

$$\frac{d\mathbf{v}_i}{dt} = \frac{\mathbf{F}_{i,d}}{m_i} \quad (7)$$

and

$$\mathbf{F}_{i,d} = \mathbf{F}_{i,drag} + \mathbf{F}_{i,g} = C_D A_f \frac{\rho_g |U_i|}{2} U_i + \rho_p V_p g_i \quad (8)$$

where C_D is the drag coefficient, $A_f = \pi r^2$ is the particle's frontal area (and r is the radius of the particle), ρ_g is the gas density, ρ_p is the particle density, V_p is the particle volume, and g_i is the gravitational acceleration in the i -th direction. U_i is the particle-gas relative velocity in the i -th direction given by:

$$U_i = u_i + u'_i - v_i \quad (9)$$

where u_i and u'_i are the local mean and turbulent fluctuating gas velocities in the i -th direction, respectively. Equation 7 can be expanded as follows:

$$\frac{d\mathbf{v}_i}{dt} = \frac{3}{8} \frac{\rho_g}{\rho_p} C_D \frac{|U_i|}{r} U_i + g_i \quad (10)$$

Only the Stokes drag is considered for the drag force (Liu et al., 1993), since the small aerosols are close to spherical shape and fixed in size (no distortion or break-up). The Reynolds Averaged Navier-Stokes (RANS) turbulent simulations are conducted with the $k - \epsilon$ model (Shih et al., 1995) for the Eulerian gas-phase flow, along with the O'Rourke turbulent dispersion model (O'Rourke, 1989) for the Lagrangian particles.

2.2. Geometry and computational mesh

The confined space of the classroom contains both the student as well as the teacher, or only the student depending on the case. The geometry details were obtained from the University of Minnesota (UMN) School of Music. This classroom is frequently used for one on one tutoring sessions or solo practise sessions for the students, and is hence very vital to the school. The dimensions of the domain are shown in Fig. 1, the labeled objects (piano, student, teacher, purifier etc.) are shown in Fig. 2a, and the locations are shown in Fig. 3. The humans are 1.6 m tall (with the injectors located around 1.5 m high), with the aerosol injection being either from an wind instrument (Trombone or a Trumpet), or directly from the nose. The instrument has an outflow diameter of 10 cm and a length of 50 cm. In the singing case, the singer's mouth is 4 cm in diameter. For the piano case, the injection cavity (which is the nose during normal breathing) is from a 1.25 cm diameter orifice.

Table 1 lists all corresponding dimensions of the domain parameters. A structured rectangular mesh was generated using CONVERGE CFD 2.4. Mesh refinement has been applied at certain boundaries, as well as the particle ejection region in front of the aerosol emitter (Fig. 4). A base grid size of 0.05 m was used at the more open areas of the domain, while smaller grid sizes of 0.0125 m and 0.025 m were used in the refined regions. The total number of cells were 400,000. A minimum time step of 0.005 s was used (a variable time step algorithm keeps the time step within 0.005 – 0.01 s).

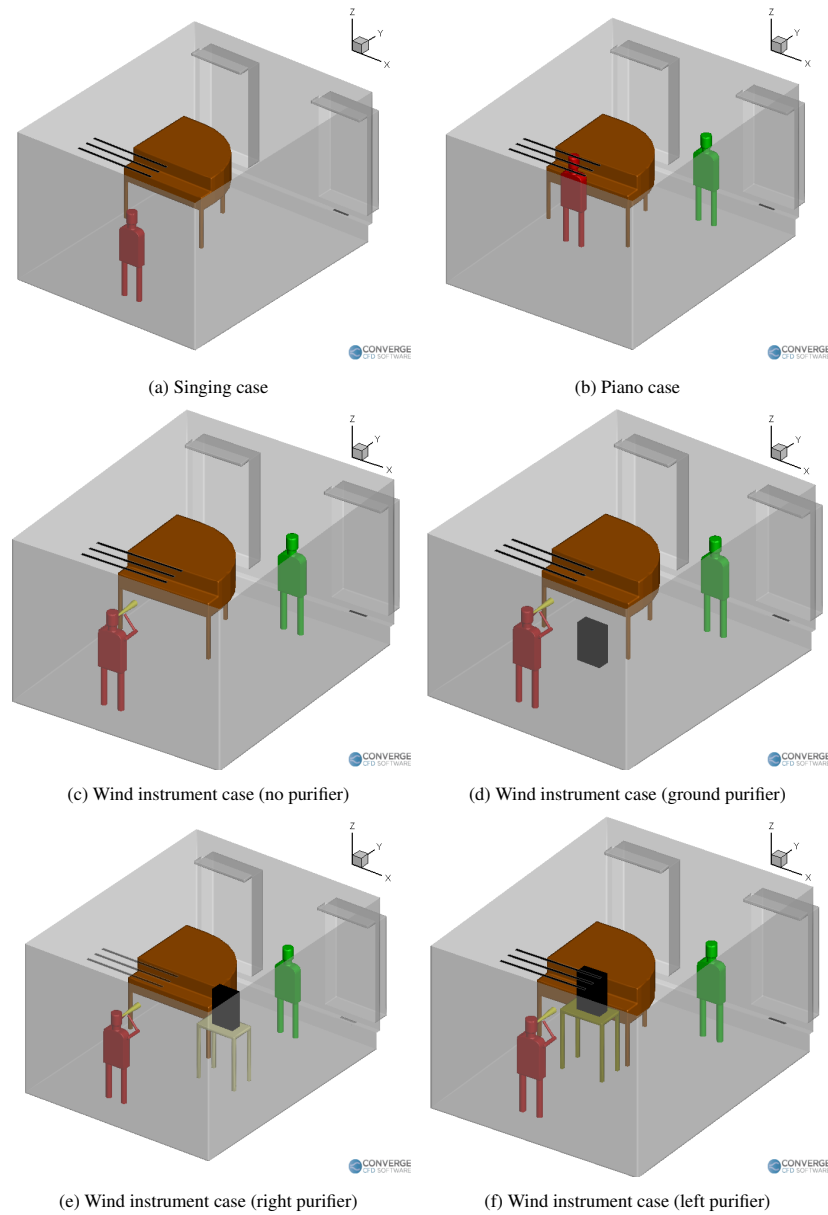


Figure 1: Different settings used in the study. The purifier in (d) is denoted by the black cuboid on the ground. The purifier is located on the table in (e) and (f).

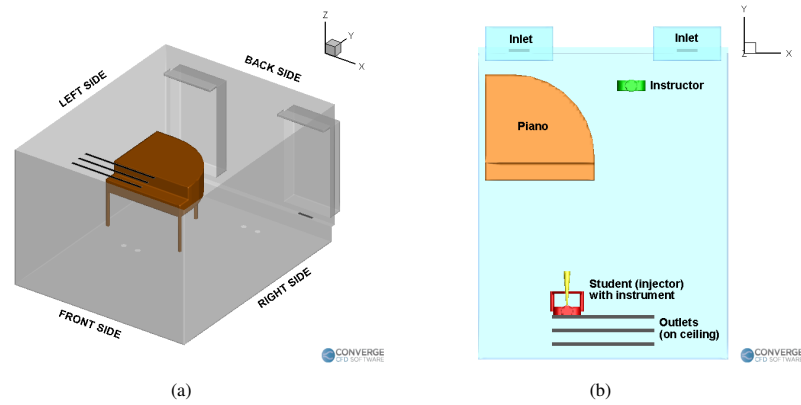


Figure 2: (a) The orientation of the domain. (b) The labeled objects in the domain.

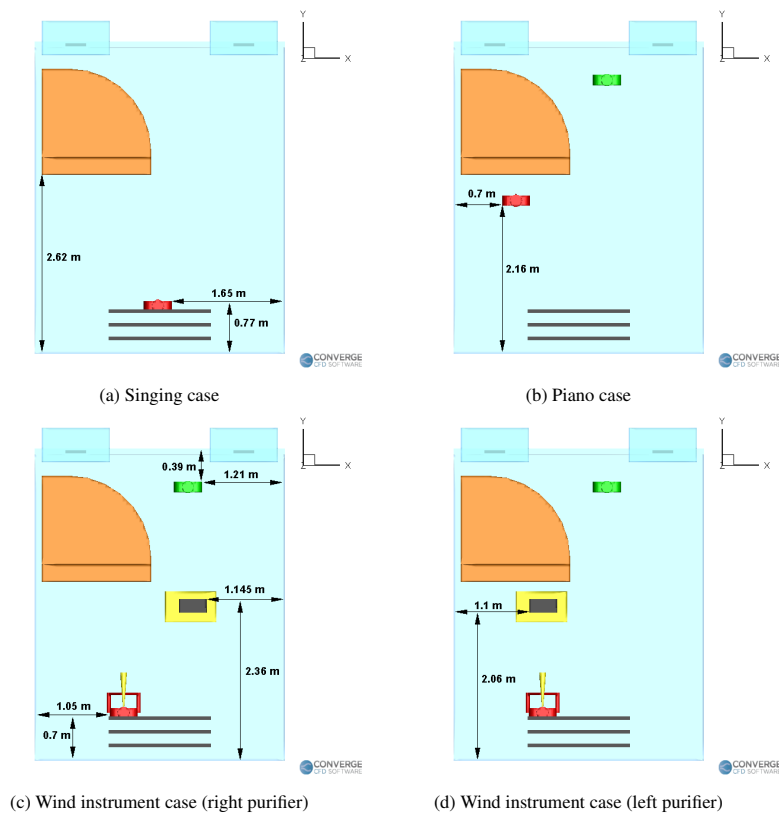


Figure 3: Locations of the student, teacher and purifier in the different scenarios. The ground purifier case is not shown here since it is located in the same spot as the left purifier, but on the ground.

Table 1: The dimensions of important objects in the domain (X - Y - Z).

Object/ surface	Dimensions [m] X - Y - Z
Room	3.657 - 4.472 - 2.743
Inflow vents	0.3 - 0.05
Outflow vents	1.5 - 0.05
Piano	1.55 - 1.55 - 1.2
Purifier	0.4064 - 0.2032 - 0.638
Table	0.75 - 0.45 - 1.0
Human	0.4 - 0.15 - 1.6

2.3. Boundary Conditions

The no slip boundary condition is applied at all solid surfaces (except the vents). Aerosols stick to the boundaries upon contact. At the ventilation air inlets, a constant mass flow rate of 0.05663 kg/s (which corresponds to an Air Change per Hour, ACH, of 3.63, or a Cubic Feet per Minute, CFM, of 100) is applied, with a zero normal gradient for pressure. These values were obtained from the technicians in the UMN School of Music. At the air outlets, a zero normal gradient condition was applied for velocity, while a constant outlet pressure of 1 atm was specified. The temperature was specified to have a uniform value of 300 K throughout the domain. The purifiers have a constant suction rate of 0.1046 kg/s (190 CFM or an ACH of 6.76), based on the CFM specifications of a standard Fellowes AeraMax 209 purifier (Fellowes.com).

3. Results and Discussion

The simulation results of the different case settings are presented and discussed in this section. Three major effects are examined in this study, namely the effect of an air purifier and its placing, the improvement in ventilation, and the effect of different aerosol injection rates. There are 3 types of musical sessions taking place: 1) a student playing a wind instrument inside the room with the teacher present; 2) a student singing alone in the room; and 3) a student playing the piano with a teacher present in the room.

For the wind instrument and piano cases, the simulation time is 660 seconds (with an initial minute of pure airflow). For the singing cases, the simulation time is 2,160 s, with 600 s of injection and 1,500 s of idle time. The initial minute of pure airflow is present for the singing cases as well.

3.1. Effect of Purifiers

In this first scenario, the student is playing a wind instrument (trombone), with the teacher present at the opposite end of the room. The aerosol injection rate is 30 aerosols/s as taken from He et al. (2020), with an airflow rate of 600 mL/s from the instrument (Fréour et al., 2010). The initial one minute of simulation was conducted without any aerosol injection, and with just pure airflow from the vents. This was to let the airflow field develop into a “statistically stationary” state, into which the

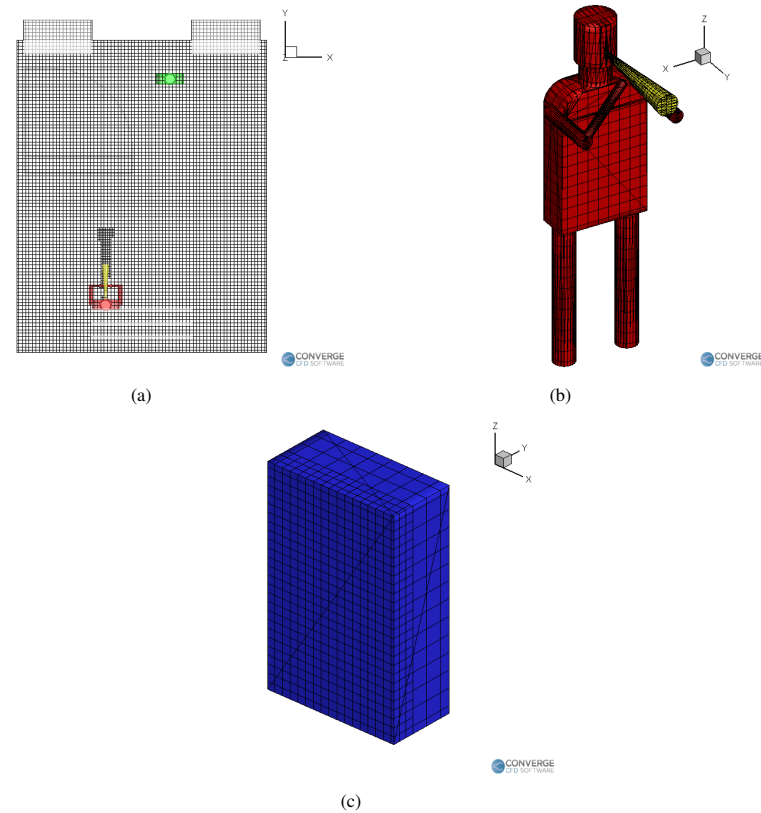


Figure 4: Mesh refinement on (a) the region in front of the injector, (b) the student, and (c) the purifier.

aerosols were subsequently injected. Purifiers are switched on right from the start of the simulation, and run throughout the entirety of the performance. The purifier is placed at three different locations: 1) on the ground in front of the student, to the left side; 2) at an elevation of 1 m in front of the student, in the same left side spot as the purifier on the ground; and 3) at an elevation of 1 m in front of the student, but on the right side.

3.1.1. Natural ventilation performance of the room - no purifier case

In this section, we first analyze the natural ventilation of the room, without any purifiers. As mentioned at the start of this section, this is a case where the student is playing a trombone in the presence of a teacher. This serves as the benchmark to compare with the purifier cases later on.

Figure 5 shows the aerosol profile at various times during the simulation. A key observation is that the aerosol cloud is shifted towards the left side of the room, where the airflow drives the aerosols beneath the piano, and through the other side. This is due to the streamlines in the domain (see Fig. 6), which visibly flow towards the left

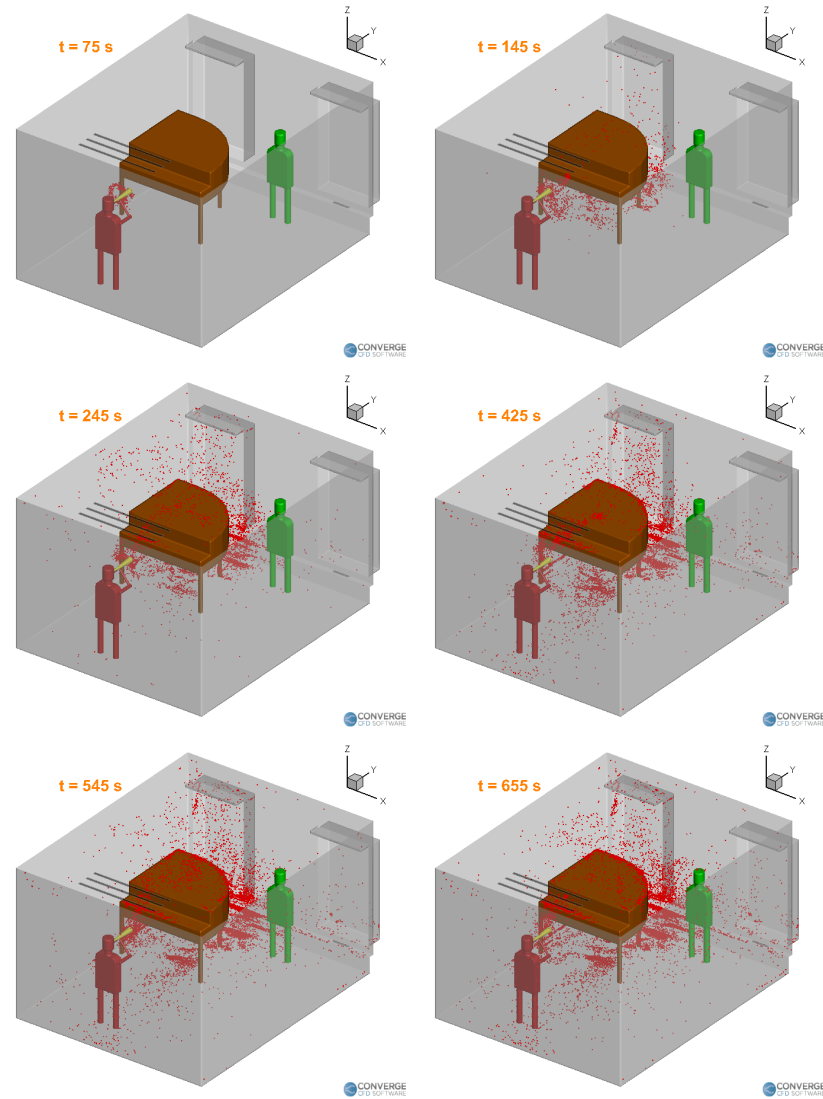


Figure 5: Aerosol profiles at various time instances inside the room.

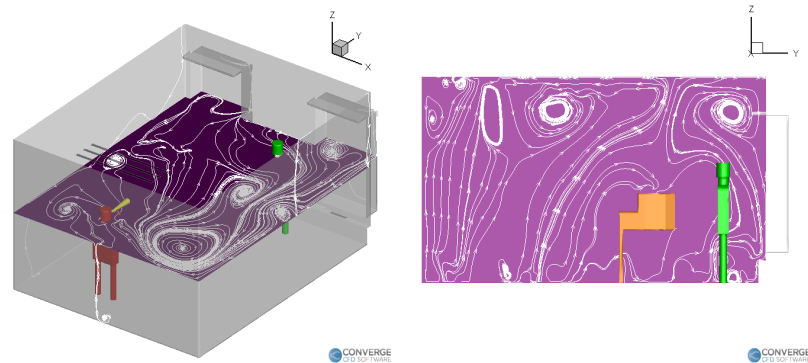


Figure 6: Airflow streamlines inside the room without a purifier.

side of the room from the right. A reason for this could be the obstruction of airflow from the inlets at the left side of the room by the huge piano, causing recirculation zones to develop near the center of the room. The right side of the room has no such large structure, and the flow profile develops without any obstruction. The airflow from the inlets push the aerosols upwards towards the ceiling, while the outlets on the ceiling pull the aerosols from the back of the room to the front. This causes a vertical recirculation zone to develop, which pushes aerosols underneath the piano, towards the ceiling near the windows, and back to the outflow vents on the ceiling near the student (Fig. 6).

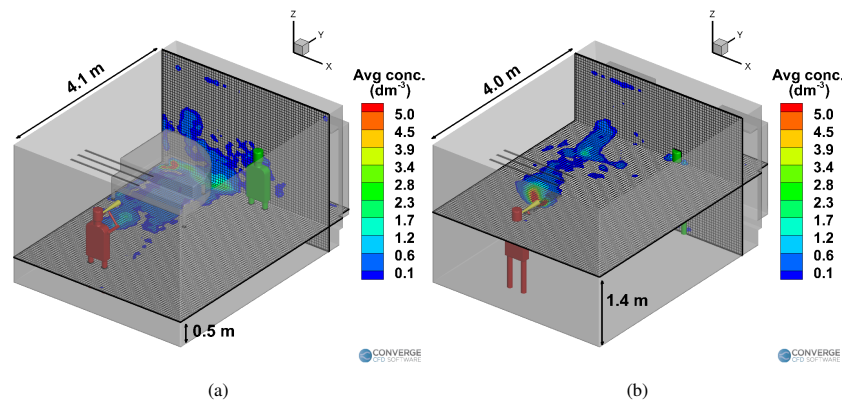


Figure 7: Time averaged aerosol concentration (per cubic decimeter) in the room at (a) Slices showing areas of greater spread of aerosols (b) Slices at elevations near the head-level of the student and injector

Figure 7 shows the time averaged airborne aerosol concentration (per cubic decimeters) at certain elevations of interest. In Fig. 7a, the Z-plane slice is located at a height of 0.5 m from the ground, while the Y-plane is located at a distance of 4.1 m from

the front of the room. A fairly widespread region of aerosol presence is observed underneath the piano, as well as behind the piano. This is due to the airflow streamlines carrying the aerosols through these regions, as shown in Fig. 6. In Fig. 7b, the Z-plane slice is located at a height of 1.4 m, while the Y-plane slice is located at a distance of 4.0 m from the front of the room (this almost coincides with the plane of the teacher's nose and mouth). There is a region of aerosol presence above the piano, owing to the streamlines and recirculation zones above the piano. In general, it is observed that the left side of the room experiences a higher concentration of airborne aerosols than the right side of the room. This result is consistent with the observations made earlier regarding the airflow field. The teacher is situated at a location slightly closer to the right side of the room, but is still exposed to a few airborne aerosols. We conclude that the teacher needs to be situated as close to the right side of the room as possible, since the risk of encountering airborne aerosols is significantly reduced there.

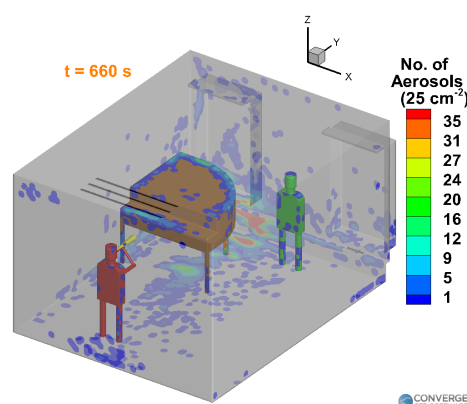


Figure 8: Aerosol deposition per unit cell area 25 cm^2 in a room without a purifier.

Figure 8 shows the total deposition of the aerosols onto surfaces per 25 square centimetres (the surface area of a $5 \times 5 \text{ cm}$ cell). A significant portion of the aerosols are visibly deposited onto the left side of the room, especially on the piano, the floor underneath the piano and the vent strip running at the back of the room. The left side window also experiences more deposition than the right side. We can observe that the teacher does experience some deposition onto their clothes, albeit slightly. This result dictates which surfaces of the room need to be cleaned thoroughly, especially the regions around the piano.

In general, we can first conclude that the airflow streamlines inside a domain significantly affect the transport of the aerosols. Moreover, the presence of any large objects which can obstruct the flow of the inlets (in this case, the piano), will alter the streamlines drastically. Obstructing the inlet airflow would lead to recirculation zones near these objects, which can cause deposition of aerosols near those objects. Regions which are fairly free from such large objects (in this case, the right side of the room) do not experience significant deposition.

Figure 9 displays the time varying profiles of the number of airborne and deposited

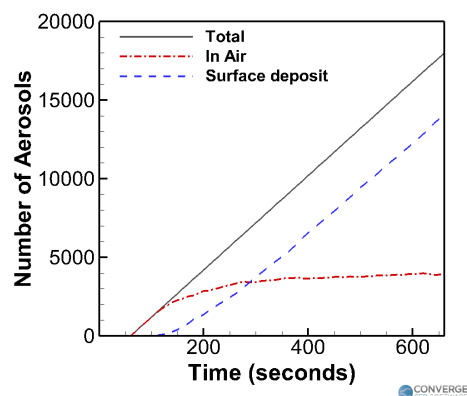


Figure 9: Temporal profiles of the aerosols in the room (without a purifier) classified into different types.

aerosols. It is observed that the number of airborne aerosols roughly flattens out around the 5 minute mark, where the number of deposited aerosols overtakes the number of airborne aerosols. Further injection of aerosols primarily causes the deposited number to grow, with little increase in the number of airborne aerosols. A total of 18,000 aerosols injected into the domain for the given time. A final aerosol deposition percentage of around 77.78% (or 14,049 aerosols) and an airborne aerosol percentage of 22.22% (or 3,951 aerosols) are observed, which are close to the observations in our previous work for another classroom with a very different size and configuration Shao et al. (2020). Moreover, an almost zero aerosol removal by the vents was observed for this case, supporting the fact that the in-built HVAC of the classroom is insufficient.

3.1.2. Student playing a trombone - Effect of purifier and purifier location

In this section, three different purifier arrangements are analyzed - purifier placed on a table on the left, purifier placed on a table on the right, and a purifier placed on the ground on the left. The elevations (achieved by using a table) are 1 m high. The purifier is a Fellow's AeraMax 290 air purifier with a CFM of 190 (around 0.1046 kg/s or an ACH of around 6.76). One assumption we make is that the purifiers remove all the viral aerosols when passed through the HEPA filter. This assumption is justified, since HEPA filters are required to have at least 99.97% (or higher) removal efficiencies for particles larger than $0.2 \mu\text{m}$ (Christopherson et al., 2020).

Figure 10 compares the deposition profiles of the aerosols onto the surfaces of the domain in the four cases (three purifier arrangements, and the case without a purifier). There seems to be a visible reduction in deposition for the purifier on the ground case. However, the purifier on the right side case has a drastically different deposition profile (Fig. 10c), where most of the deposition is limited to the edge of the walls near the piano.

The deposition pattern is largely affected by the airflow streamlines in the room. The presence and location of the purifier largely affects the airflow streamlines, which in turn affect the deposition and airborne concentration of the aerosols. For the case

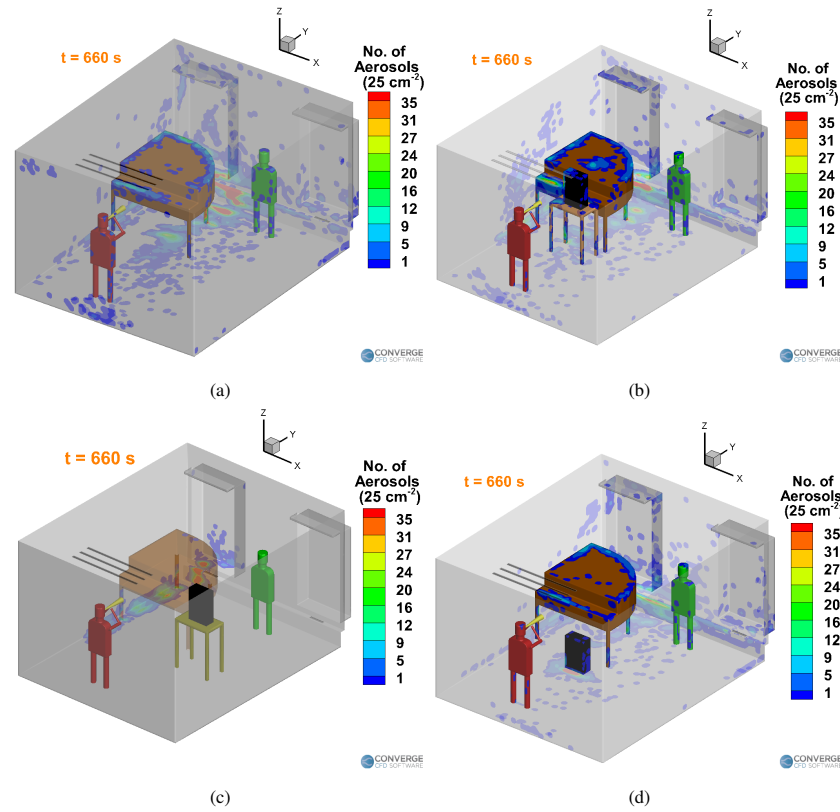


Figure 10: Deposition trends for the wind instrument (trombone) case with (a) No purifier (b) purifier on the left side at an elevation; (c) purifier on the right side at an elevation; and (d) purifier on the ground.

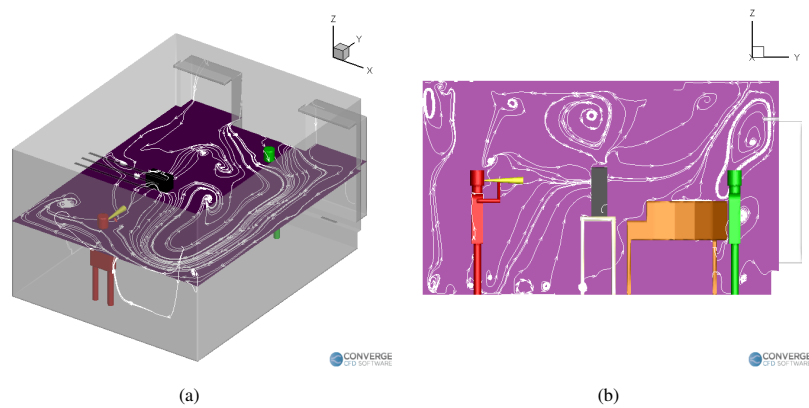


Figure 11: Airflow streamlines inside the room with a purifier on the left table: (a) horizontal plane; (b) Vertical plane.

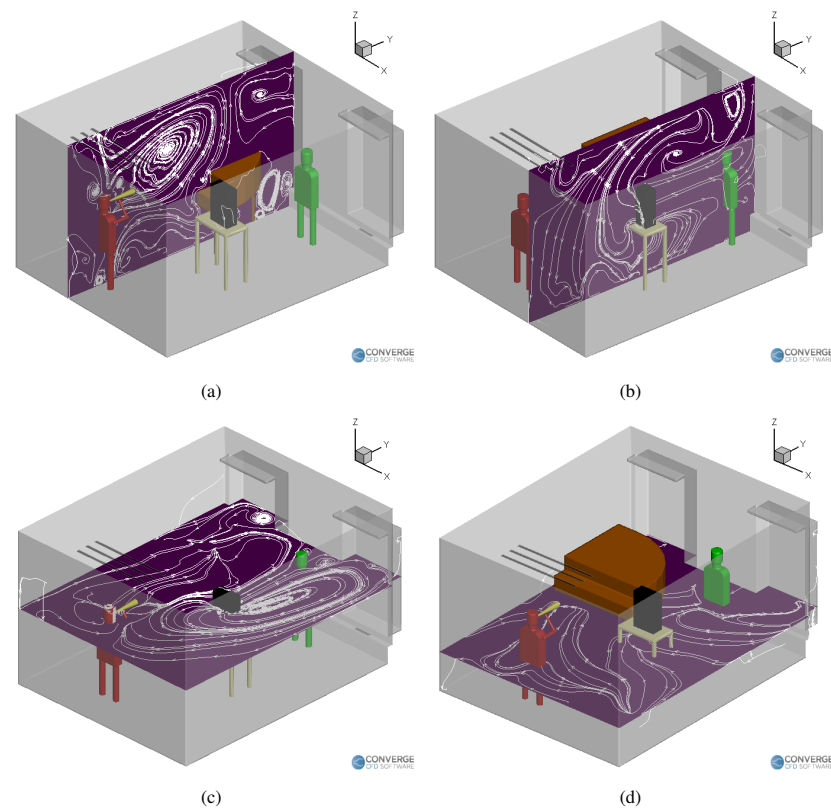


Figure 12: Airflow streamlines inside the room with a purifier on the right table: (a) and (b) are vertical planes; (c) and (d) are horizontal planes. Two sets of slices are taken to show the difference in streamlines near and away from the injector location, as the purifier is far away from the injector in this case.

with the purifier on the left side (at an elevation), the purifier's suction side directs the airflow streamlines (Fig. 11) towards the center of the room, while the exhaust of the purifier quickly blows away the aerosols towards the rear side of the room (and towards the teacher). This "boost" zone behind the purifier serves to accelerate the deposition of aerosols on top of the piano, as seen in the deposition profile (Fig. 10b). Figure 12 shows the airflow streamlines in the room due to the presence of the purifier on the right side of the room, at an elevation. We can immediately see that the presence of the purifier on the right side drastically changes the streamline profiles. The horizontal recirculation zones no longer extend all the way from the right side to the left side, as seen in the previous case. Instead, the streamlines divert towards the center-right portion of the room, where the purifier is located (Fig. 12c). The aerosols at this elevation (near the injector) subsequently tend to flow to lower heights due to the weaker airflow velocity on the left side. At the lower elevations where the purifier's influence is weaker, the streamlines do extend all the way to the left side of the room

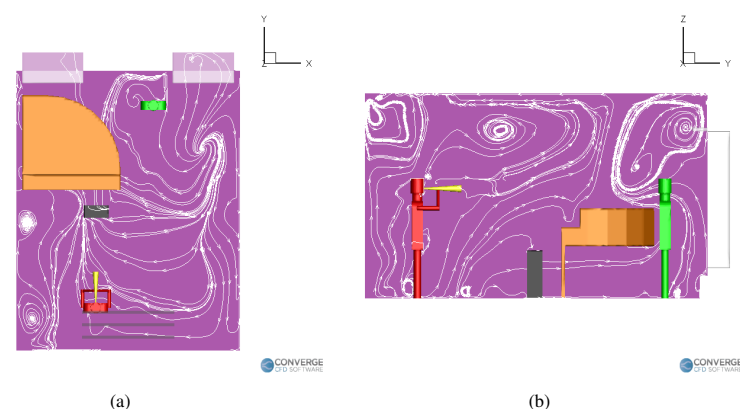


Figure 13: Airflow streamlines inside the room with a purifier on the ground: (a) Horizontal plane; (b) Vertical plane.

(Fig. 12d). Due to this, the aerosols tend to be deposited onto the extreme left side of the wall once they settle to the low elevation. The horizontal streamlines for the purifier on the ground case (Fig. 13a) also extend from the right side to the left. Moreover, the exhaust of the purifier directs the airflow underneath the piano (Fig. 13b), which then flows upwards behind the piano to create a strong recirculation zone there, which causes aerosols to deposit near the center of the piano (Fig. 10d). The purifier on the left table case has a similar recirculation zone on top of the piano (Fig. 11b), but it is smaller than the recirculation seen in Fig. 13b. We can see some of the streamlines flowing right onto the center of the piano, which causes some deposition near the center of the piano (Fig. 10b).

In general, we can comment that purifiers are significantly going to affect the airflow streamlines in the room, which in turn will affect both deposition, the airborne concentration profiles, as well as the removal of the aerosols through the vents/purifiers. It is recommended to place the purifier in a location which does not disrupt the natural airflow streamlines in the room in a negative way (the exhaust of the purifier should not cause more mixing/spreading of the aerosols). An example of proper purifier placement can be found in the purifier on the ground case, where the airflow streamlines from the exhaust of the purifier follow a path underneath the piano (Fig. 13b), which is similar to the case without a purifier (Fig. 6). Hence, there is not significant spreading of aerosols in this case. On the other hand, in the purifier on the left side case, the purifier's exhaust causes airflow streamlines above the piano (Fig. 11b) which causes more mixing and hence, slightly more deposition onto the teacher (Fig. 10b).

Figure 14 compares the temporal profiles of the number of aerosols among the different purifier cases. Figure 14b shows the plot of the different time-varying aerosol numbers for the left table purifier case. Like in the case without a purifier (Fig. 14a), the number of airborne aerosols seems to flatten out around the 5-minute mark. However, the number of airborne aerosols in this case has reduced, fluctuating about a mean value of around 3,219 aerosols (17.88%). The number of aerosols filtered out grows as

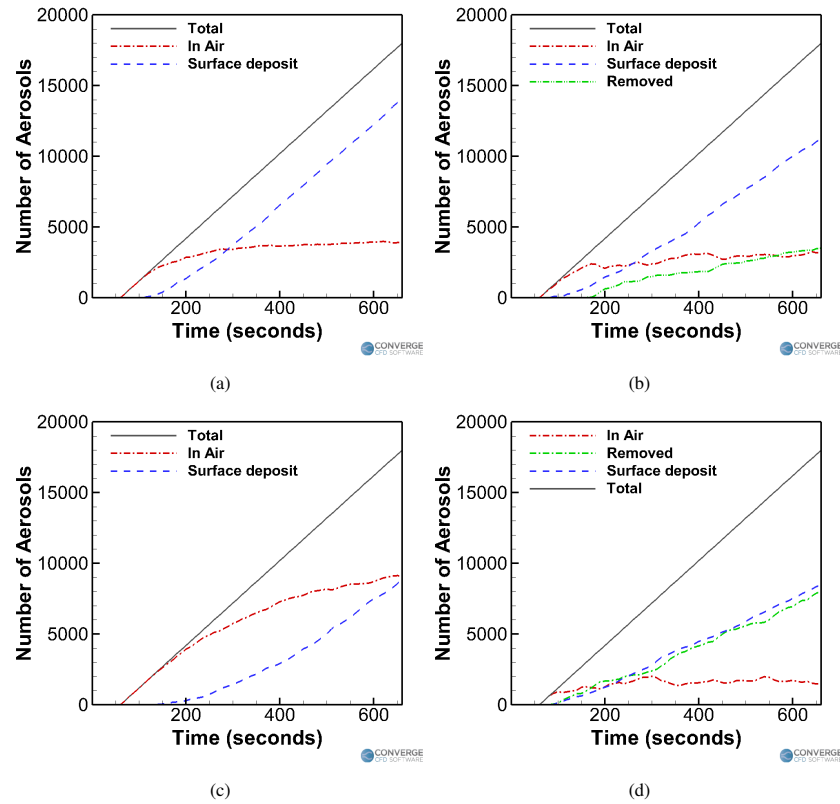


Figure 14: Temporal profiles of the aerosols in the room for the wind instrument (Trombone) case with (a) No purifier (benchmark) (b) Purifier on the left side at an elevation; (c) Purifier on the right side at an elevation; (d) Purifier on the ground.

well, reaching a value of roughly 3,530 aerosols (19.6%) at the end of 10 minutes. The number of deposited aerosols has also reduced from the previous case, reaching a value of around 11,249 aerosols (62.5%). The purifier does help in reducing both the airborne aerosol concentration and the aerosol deposition (see Fig. 15a and Fig. 15b). However, the improvement seems to be minor and not effective enough to warrant this purifier setting to be the optimal location. Figure 14c shows the time varying aerosol profiles for the purifier on the right side table case. Interestingly, the number of aerosols in the air has actually increased significantly (9,093) from the case without a purifier (3,951) (see Fig. 15a). Furthermore, almost no aerosols are removed by the purifier, making this arrangement is quite dangerous. Figure 14d shows the time varying aerosol profiles for the purifier on the ground case. A significant difference is observed between this case and the previous two cases. The number of airborne aerosols has been reduced to almost 1,534 (8.52%) which also remains fairly constant since the 5 minute mark. The number of deposited aerosols has also been reduced to 8,465 (47%), while the number

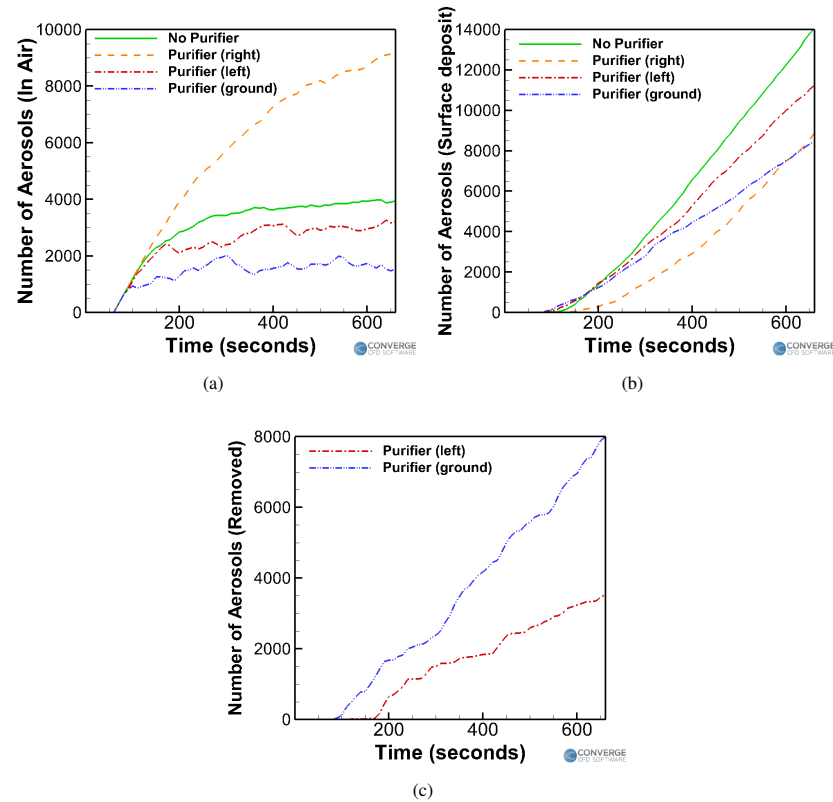


Figure 15: Trends comparison for the wind instrument case: (a) aerosols remaining in the air; (b) aerosols deposited onto surfaces; (c) aerosols removed via vents and purifiers.

of aerosols filtered out by the purifier has increased significantly to 8,001 (44.4%). This grounded location of the purifier has served to be the best one so far. It lies naturally in the path of the ejected aerosols, and is also more isolated from the teacher due to it being hidden away underneath the piano. As a result, it offers the best reduction in airborne and deposited aerosol numbers compared to the no purifier case (see Fig. 15a and Fig. 15b). It even offers a higher aerosol removal rate than the other two purifier cases, as seen in Fig. 15c.

It is observed that for all these cases, the number of aerosols remaining in the air more or less oscillates about a mean value after an early transient period (observed to be around 5 to 6 minutes). Any simulation time greater than the initial transient period will produce results which will vary quantitatively but not qualitatively.

Figure 16 compares the time averaged airborne aerosols concentration at elevations of interest, inside the classroom between the no purifier benchmark case (Fig. 16a) and the remaining cases with purifiers. It is observed that the adding a purifier helps in reducing the airborne concentrations at the elevations of interest (a height of 1.4 m

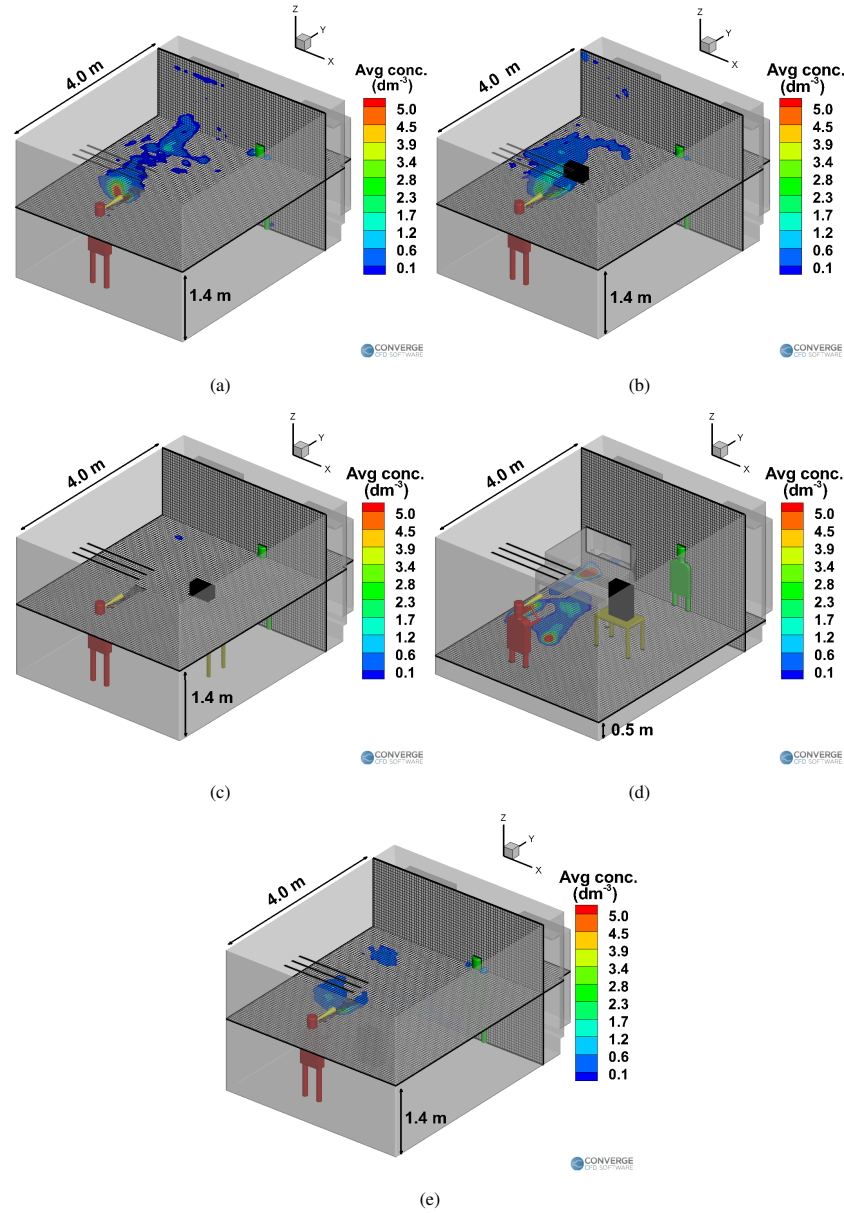


Figure 16: Time averaged airborne aerosol concentrations (per cubic decimeter) for the wind instrument (trombone) case with (a) no purifier; (b) purifier on the left side at an elevation; (c) purifier on the right side at an elevation (slice elevation near the injector); (d) purifier on the right side at an elevation (slice elevation at a lower height); and (e) purifier on the ground.

and a distance of 4.0 m from the front side). The purifier on the left side causes more spreading of the aerosols onto the walls at the left (Fig. 16b) due to the airflow streamlines. The purifier on the ground further reduces the airborne aerosol concentration, as seen in Fig. 16e. This is because the purifier is kept in a location such that it offers the maximum removal of aerosols. The purifier on the right case is a strange case; although it does reduce the aerosol concentrations at the elevations near the injector (i.e., a height of 1.4 m), there is actually a higher number of airborne aerosols when compared to any of the other case (including the no purifier case), as seen in Fig. 14c. Most of these airborne aerosols are in fact located in the region underneath the piano, as seen in Fig. 16d. This situation could be dangerous when the purifier is switched off, as these airborne aerosols might once again follow the natural recirculation streamlines underneath the piano and enter the space next to the instructor again. Moreover, this case offers zero removal of aerosols by the purifier, which again defeats the purpose of having a purifier in the first place.

3.1.3. Student singing alone (no teacher, with a no people break in between) - Effect of the purifier

In this section, the benchmark singing case (without a purifier) is compared to the case with a purifier. The student (located exactly at the center underneath the return vents) is singing inside an empty room for a total duration of 10 minutes. There is then a break for 25 minutes (during which time the student is not present in the room) and the airborne aerosols are allowed to settle and deposit, such that the room can be safer before the next person's arrival. It is of interest to examine the number of remaining airborne aerosols in the room. The rate of aerosol injection is 700 aerosols/s (Alsved et al., 2020), with an airflow rate of 0.2 L/s (Salomoni et al., 2016; Jiang et al., 2016). It is of interest to note that singing has a slightly larger particle injection rate (700 aerosols/s) when compared to normal speaking (570 aerosols/s) as found in Alsved et al. (2020).

Figure 18 shows the airflow streamlines inside the room for the singing without a purifier case. Similar to the previous scenarios, the streamlines flow from the right side of the room to the left side, creating recirculation zones at different locations on the left side of the injector. Figure 19 shows the streamlines inside the room for the singing with a purifier case. We can see that the recirculation zones forming on both the vertical plane (going over and below the piano) and the horizontal plane (going from the right side to the left side of the room). These streamlines are different from the case where there was no purifier, which is expected, since the airflow rate of the purifier is higher than the existing building HVAC ventilation airflow rate. The purifier therefore drives the airflow streamlines in the domain, especially in the region near the injector.

Figure 20 compares the deposition of the aerosols in the domain between the singing with no purifier case (Fig. 20a) and singing with a purifier case (Fig. 20b) at the end of 36 minutes. Much of the deposition occurs on and near the piano, especially underneath the piano. Significant deposition occurs on the vent strip (containing the air inlets), as well as on the window sills. Additionally, there seems to be some deposition on the student themselves, which is an important point to consider. The clothes of the students need to be well washed to prevent further risk of spreading to others. It is observed that for the purifier case, there is slightly more deposition on the right side of

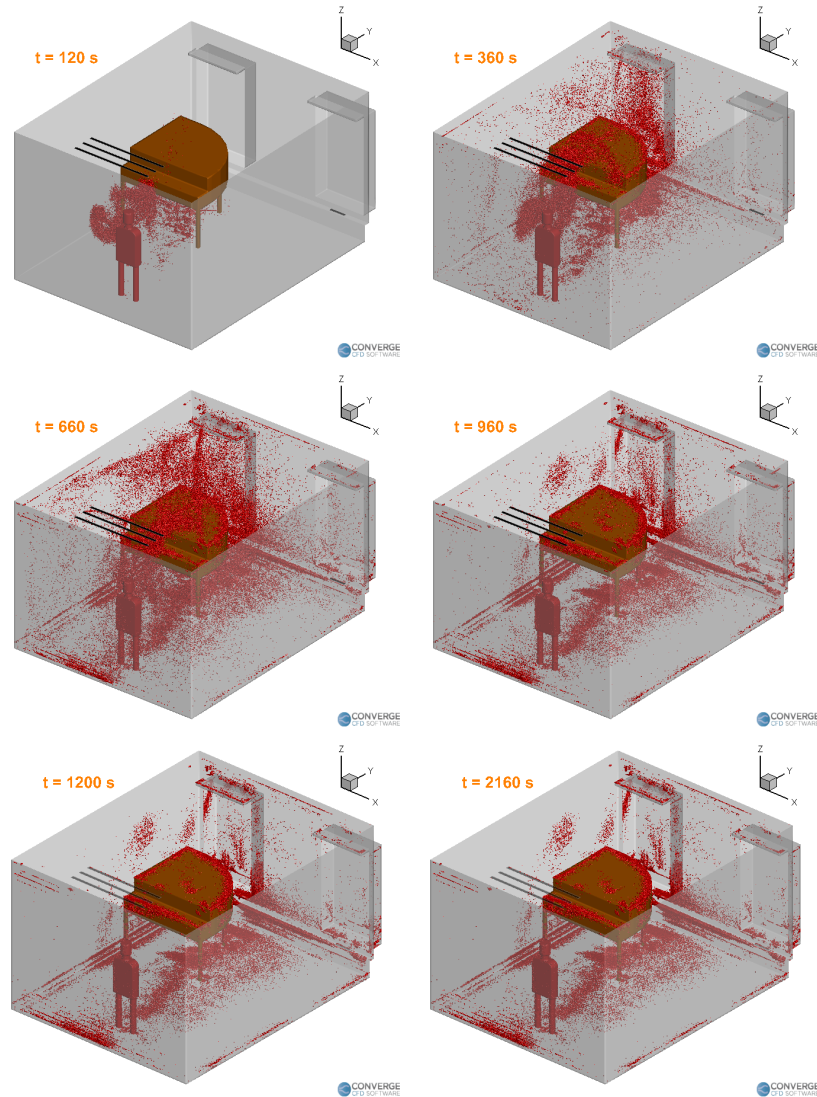


Figure 17: Aerosol profiles at various instances of time inside the room with a singer.

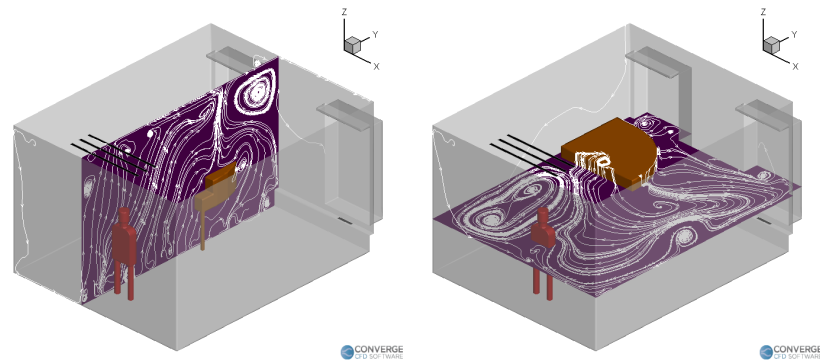


Figure 18: Airflow streamlines inside the room with a singer.

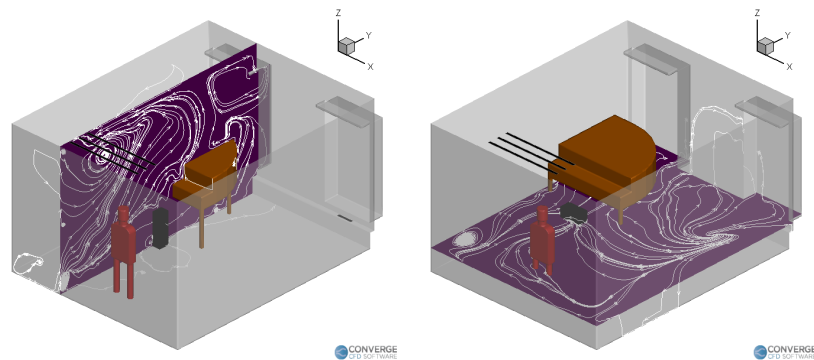


Figure 19: Airflow streamlines inside the room with a singer and a purifier.

the room, near the window. There is also slightly less deposition near the left side walls and window. The purifier increases deposition near the ground in front of it, causing less deposition on the ground near the back side of the piano. Overall, the deposition seems to be similar between the two cases.

Figure 21 shows the time varying profiles of the number of airborne, deposited and removed aerosols for the singing without a purifier case. The total number of droplets injected into the domain in 10 minutes is 420,000. The number of deposited droplets and the number of airborne droplets steadily increase up until the point when the student stops singing and leaves for the break (at the 11 minute mark). At this point, the number of deposited droplets (around 308,000 or 73.33%) significantly outnumber the number of airborne droplets (around 112,000 26.66%). Following this, the airborne aerosol number gradually plummets, while the number of deposited droplets slowly increases. Around the 30 minute mark, the number of airborne and deposited droplets roughly flatten out at values of 8,724 (2.07%) and 411,108 (97.8%), respectively. The number of aerosols vented out (168 or 0.04%) is orders of magnitudes lower than both

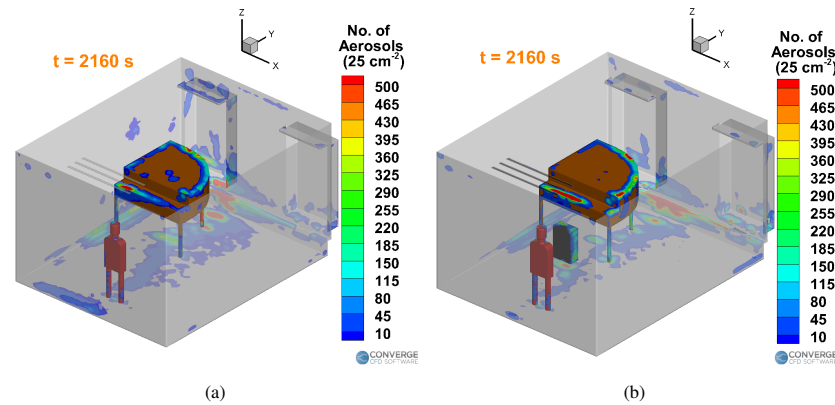


Figure 20: Aerosol deposition per unit cell area (25 cm^2) inside the room with a singer: (a) no purifier; (b) with a purifier.

the airborne and deposited modes. Further airborne aerosol reduction seems to either not happen at all, or it happens at an extremely slow rate (~ 1 aerosol per 10 s). This could be due to the stable trapping of the aerosols in the recirculating streamlines in the room, which prevent the aerosols from depositing or being vented out. Hence, the maximum possible aerosol removal in this case seems to be around 103,300 (92% with an airborne aerosol number of 8,700 at the end of 35 minutes).

Figure 22 shows the time varying profiles of the number of airborne, deposited and removed aerosols for the singing with a purifier case. Like before, the number of airborne and deposited aerosols steadily rise until the 11 minute mark, at which point the student stops singing (and leaves the room to take a break). The number of airborne aerosols at this point in time is around 114,888 (27.35%), while the number of deposited aerosols is around 288,721 (68.74%). The number of aerosols removed from the domain in the first 11 minutes is around 16,354 (3.9%). Following this, there is a sharp descent in the number of airborne aerosols, followed by a sharp rise in the number of aerosols removed from the domain. Interestingly, unlike the case without a purifier, the number of airborne aerosols keeps decreasing at a steady rate of around 2 - 5 aerosols/s. At the end of 35 minutes, the number of airborne aerosols has reduced to 4,333 (1.03%), while the number of deposited aerosols has increased to 386,611 (92.05%). The number of aerosols removed has reached a nearly steady value of 29,006 (6.9%).

Figure 23 summarizes the effect of having a purifier in the singing case. For both the singing cases, the number of airborne aerosols fluctuates about a mean value, at around the 500 second mark. The number of aerosols remaining in the air at the end of 35 minutes (Fig. 23a) is smaller (by around 4,367 or 50%) for the case with a purifier. As mentioned before, this number is still reducing with time, as opposed to the case without a purifier, where the number has more or less become constant. The number of aerosols deposited onto surfaces is relatively unchanged, although it is slightly lower for the case with a purifier (Fig. 23b). Figure 23c shows that the number of aerosols

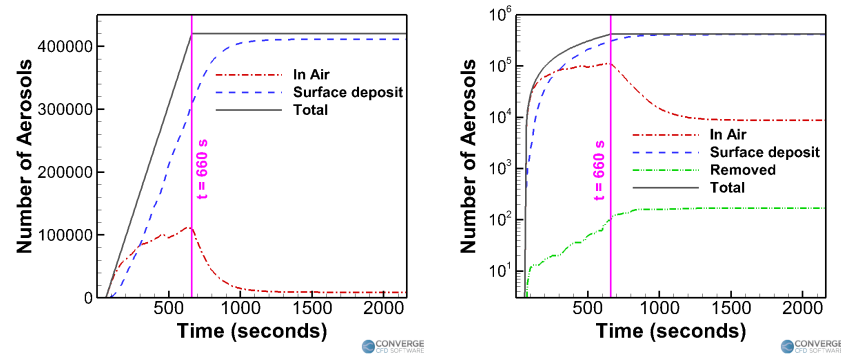


Figure 21: Temporal profiles of the aerosols in the room (singer, no purifier) classified into the number of aerosols remaining in the air, deposited onto surfaces and removed.

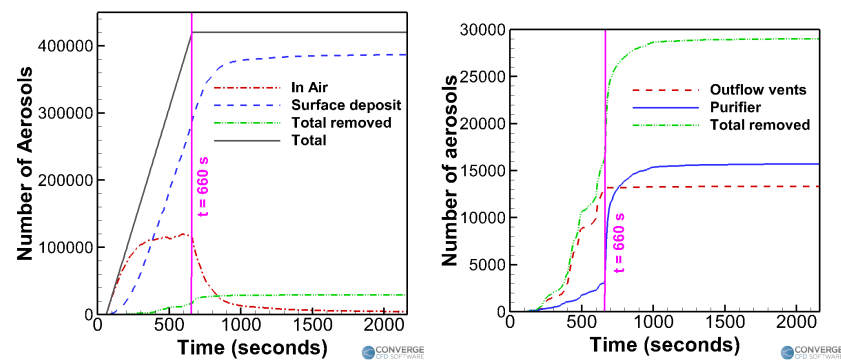


Figure 22: Temporal profiles of the aerosols in the room (singer, with a purifier) classified into the number of aerosols remaining in the air, deposited onto surfaces and removed.

removed from the domain for the case with a purifier (around 29,000 aerosols removed) is more than two orders of magnitude higher than the case without a purifier (around 150 aerosols removed).

3.2. Comparison of removal times and ventilation rates with the CDC/WHO guidelines

When not using any purifier, the existing building HVAC airflow rate of 0.05663 kg/s corresponds to a ventilation rate of around 166 m³/h, which is significantly less than the ventilation rate of least 288 m³/h per person is recommended by WHO (Chartier and Pessoa-Silva, 2009). However, adding a purifier of 0.1046 kg/s (which by itself corresponds to around 322 m³/h) increases the overall ventilation to around 488 m³/h, which is far more than the required rate prescribed by WHO.

In this section, we also examine how adding a purifier helps in achieving CDC guideline levels of removal times (Appendix B, Chinn and Schulster (2003)), as shown

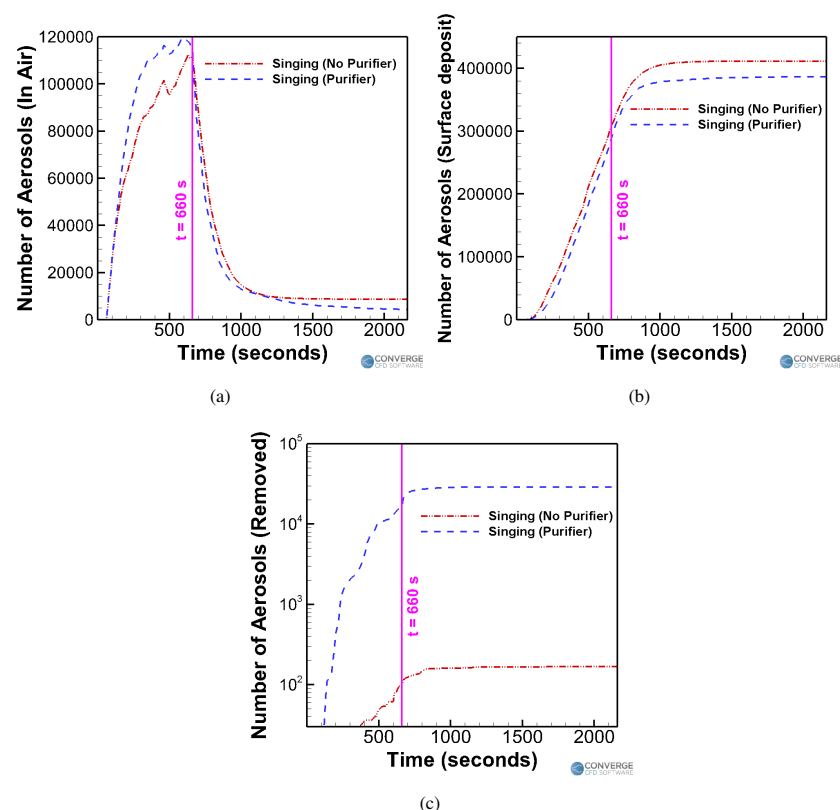


Figure 23: Trends comparison for the singing case: (a) aerosols remaining in the air; (b) aerosols deposited onto surfaces; (c) aerosols removed via vents and purifiers.

in Fig. 24. The table is valid for a room without any continuous injection, which corresponds to our singing cases (where the student stops singing and leaves the room at the 11 minute mark).

Table 2: The comparison of the removal times (with and without a purifier) to the CDC value.

ACH	Time for 99 % removal efficiency			Time for 99.9% removal efficiency		
	CDC	Purifier	No Purifier	CDC	Purifier	No Purifier
3.63	81 min	78 min	> 1 day	123 min	95 min	> 1 day

For the case without a purifier, if we expect a slow removal rate of 1 aerosol/10 s (assuming a best case), it would take around 24 hours (i.e, an entire day) to completely remove the remaining aerosols. According to the CDC guidelines for a room with an ACH of 3.63, it should roughly take around 81 minutes for 99% removal and around 123 minutes for 99.9% removal. Clearly, these numbers are very far off from the expected removal time of >24 hours. This suggests that the natural aerosol removal

ACH § 11	Time (mins.) required for removal 99% efficiency	Time (mins.) required for removal 99.9% efficiency
2	138	207
4	69	104
6*	46	69
8	35	52
10*	28	41
12*	23	35
15*	18	28
20	14	21
50	6	8

Figure 24: CDC guidelines for the Air changes/hour (ACH) and time required for airborne-contaminant removal by efficiency (Chinn and Schulster, 2003).

capacity of the classroom is not sufficient enough to effectively remove all (or most) of the airborne aerosols.

For the case with a purifier, if we assume a steady airborne aerosol removal rate of 1 aerosol/s (which is less than what was observed at the 36 minute mark), it would take around 53 minutes more (in addition to the 25 minutes duration of no injection) to reach the 99% removal stage, where only 1,149 aerosols are remaining airborne (1% of the 114,888 airborne aerosols left when the singer stops singing). It would also take 70 minutes more to reach the 99.9% removal stage, where only 115 airborne aerosols remain. Considering that 25 minutes have already elapsed since the singer stopped singing, it would take roughly 78 minutes and 95 minutes for achieving the 99% and 99.9% removal efficiency respectively, which are faster than the CDC guideline values of 81 minutes and 123 minutes, respectively.

Table 2 summarizes the aerosol removal times of the cases with and without a purifier, with the CDC guidelines. In conclusion, adding a purifier helps in improving the ventilation rate to a value above the recommended rate prescribed by WHO, while also helping in achieving aerosol removal times as prescribed by the CDC guidelines. Moreover, this helps in deciding an effective break period in between sessions of singing/instrument playing. The break period of 25 minutes used in the singing case with a purifier reduces the airborne aerosols to almost 4,333 (from 114,888), which is a reduction of almost 97%. This could serve as an effective break period even for lengthened periods of any classroom session, since it is observed that the number of airborne aerosols fluctuates about a mean value after an initial transient period of around 8 to 9 minutes (for the singing case) or 5 to 6 minutes (for the wind instrument case).

3.3. *Effect of Injection Rate: changing the instrument / using a mask / different mode of injection*

In this section, the following cases are examined and compared: 1) student playing a wind instrument (a trumpet this time) inside a room (with no purifier) with a teacher present, 2) a student singing alone in a room wearing a mask, and 3) a student playing a piano (wearing a mask) inside a room with a teacher. These are three typical scenarios encountered in a music classroom, and hence were chosen as the settings for this study. Although the cases are pertaining to a specific musical setting, the effects and analysis are not; they can be applied to any injection scenario in general. The different settings effectively just change the injection rate/flow streamlines, so that generalized observations on their influence can be made.

The trombone case (Fig. 25a) and trumpet case (Fig. 25b) are compared with each other. Injection rates of 30 aerosols/s (trombone) and 100 aerosols/s (trumpet) were assumed based on the experimental measurements (He et al., 2020), with both cases having airflow rates of 600 mL/s (Fréour et al., 2010). It is observed that the playing a trumpet causes much more aerosols to remain in the air (13,581 aerosols) compared to the trombone case (3,951 aerosols). Moreover, the number of deposited aerosols is also much higher for the trumpet case (46,416 aerosols) compared to the trombone case (14,049 aerosols). This consequently makes playing a trumpet riskier than playing a trombone. Interestingly, the number of airborne and deposited aerosols has roughly tripled in number for the trumpet case (compared to the trombone case), which is also the same scaling in the aerosol injection rate (which has roughly tripled from 30/s to 100/s).

Next, the student singing without a mask (Fig. 25c) and with a mask (Fig. 25d) are compared with each other. Injection rates of 700 aerosols/s (no mask) and 400 aerosols/s (with mask) were assumed (Alsved et al., 2020), with an airflow rate of 0.2 L/s (Salomoni et al., 2016; Jiang et al., 2016). For the first 11 minutes of simulation where the student continues to inject aerosols, it is observed singing with a mask drastically lowers the airborne aerosol number (to 60,337 aerosols, see Fig. 25d), compared to the singing without a mask case (111,943 aerosols, see Fig. 25d). The number of surface deposited aerosols within the first 11 minutes have also decreased in the masked case (to 185,561 aerosols) compared to the non-masked case (307,957). Similar to what was observed in the wind instrument case, the airborne and deposited aerosol numbers (for the duration when the student continues to inject aerosols, i.e., 11 minutes) seem to have roughly halved when the injection rate was also roughly halved (from 700 to 400 aerosols/s). Once the student stops injecting aerosols and the remaining aerosols in the air are allowed to deposit or be vented, the final aerosol numbers are 3,871 and 242,004 (in air and surface deposited aerosols respectively) for the masked singing case, and 8,699 and 411,132 (in air and surface deposited aerosols, respectively) for the no mask singing case. Again, the final ratios of these numbers are roughly 1:2 for the singing with mask to singing without mask ratio, which again is similar to the roughly 1:2 injection rate ratio of 400:700.

Lastly, the student playing a piano case is examined and compared (fig 25e) to the other cases. The student is just breathing normally, through a mask while playing the piano for a duration of 10 minutes. The aerosol injection rate is around 5 aerosols/s,

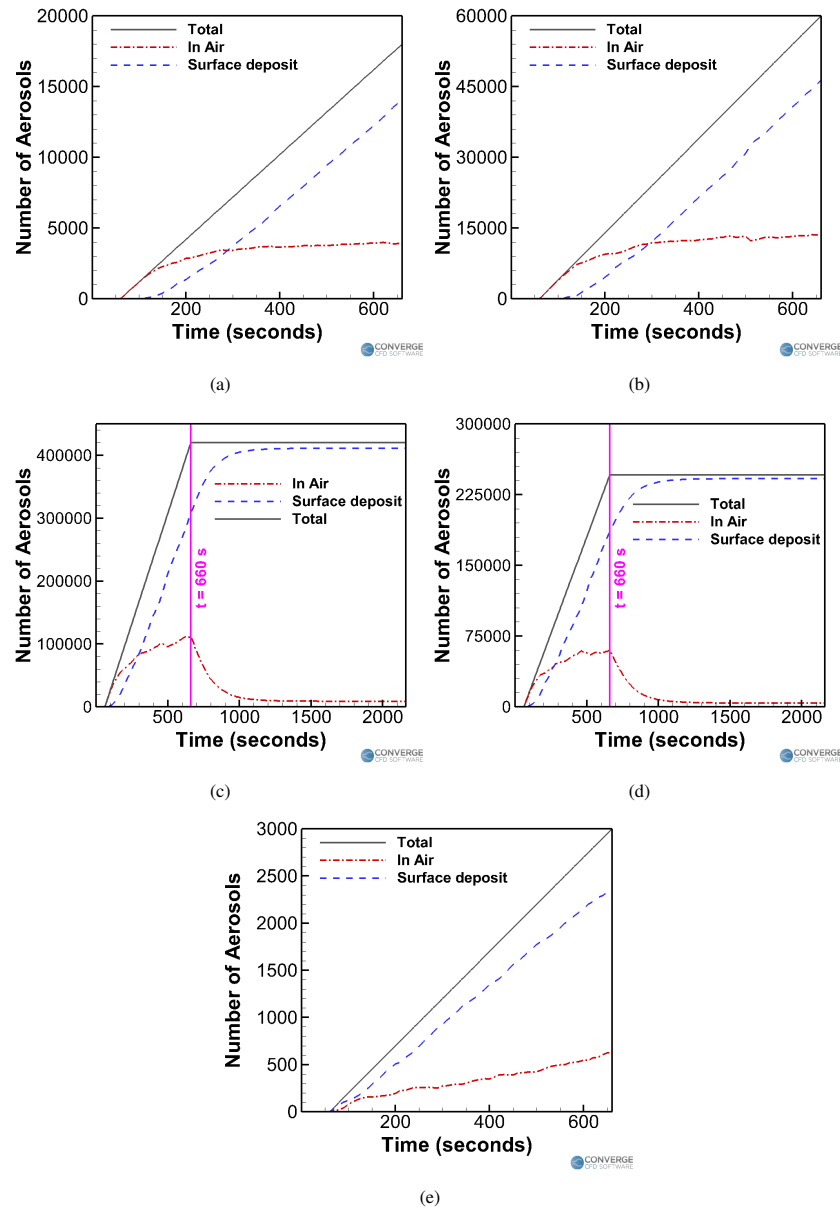


Figure 25: Effect of the injection rate on the temporal aerosol profiles for (a) the student playing a trombone case; (b) student playing a trumpet case; (c) student singing without a mask case; (d) student singing with a mask case, and (e) student playing a piano case.

assuming a 50% efficiency cloth mask (Rengasamy et al., 2010) with a normal aerosol breathing injection rate of 10 aerosols/s (He et al., 2020; Alsved et al., 2020). The exhaled airflow rate is around 0.1 L/s (Salomoni et al., 2016). This case has the least amount of aerosols in the air (623 aerosols) and deposited aerosols (2,327 aerosols) compared to the other cases, making it the least dangerous scenario by a large margin.

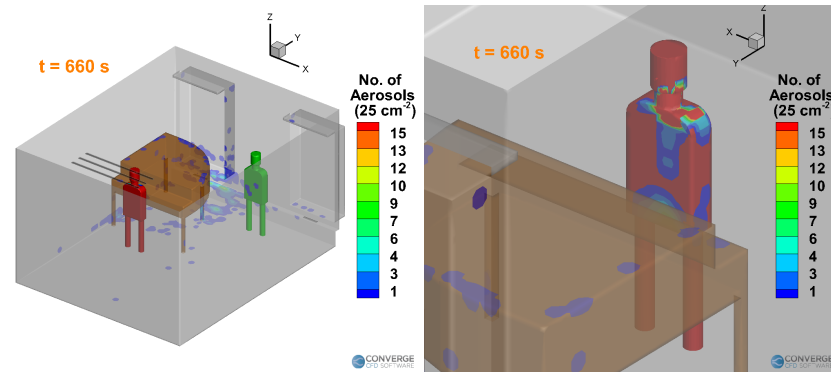


Figure 26: Aerosol deposition per unit cell area (25 cm^2) inside the room (student playing a piano).

Figure 26 shows the deposition of the aerosols onto the surfaces in the domain for the piano case. Major deposition occurs right on the student themselves, due to the low air flow rate through the mask. Further deposition occurs on the front of the piano, as well as the vent strip behind the piano. The deposition for the piano case is very less, compared to any of the singing or wind instrument cases (see Fig. 27).

3.4. Summarizing the trends overall

Figure 28 shows the trends of the airborne and deposited aerosol numbers when comparing the two types of effects - the effect of a purifier (Fig. 28a) and varying the injection rate (Fig. 28b). Although the numbers may change depending on the simulation time, the trends will hold good for any simulation time larger than the initial transient periods specified in previous sections.

Figure 28a shows the total number of aerosols remaining in the domain by the end of the simulation (in the instruments case, the simulation ends after the injection stops. In the singing cases, the simulation ends after 25 minutes of idle time after the 10 minutes of injection). The advantage of using purifiers is heavily dependent on the location of the purifier. As explained earlier, improper placement of the purifier might even make the situation worse, as is evident from the purifier on the right side case (where the resulting airborne aerosol number is almost thrice that of the case without a purifier, and almost ten times that of the case with a purifier on the ground). Using a purifier almost halves the airborne aerosol number in the case with a lone singer. Smart placement of purifiers can thus yield a huge benefit in terms of reducing the airborne aerosol number. The optimal location for purifier placement highly depends on the geometry of the domain and the flow parameters. The first and most important step in any general domain is to identify the region where placing a purifier would yield a positive

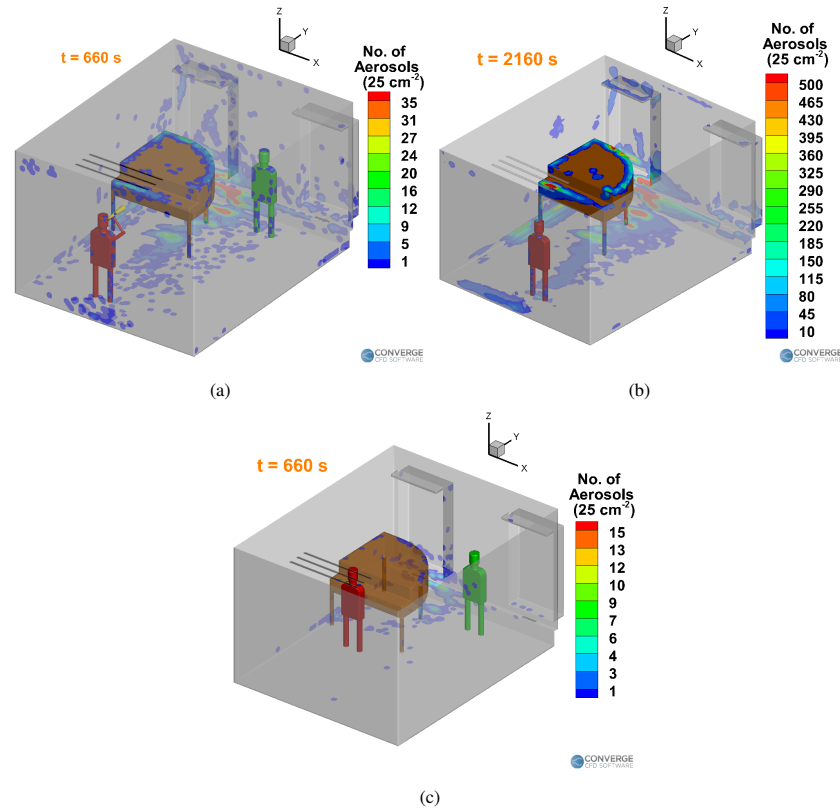


Figure 27: Comparison of the deposition of aerosols inside the domain for (a) the student playing a trombone (no purifier); (b) student singing (no purifier); (c) student playing a piano.

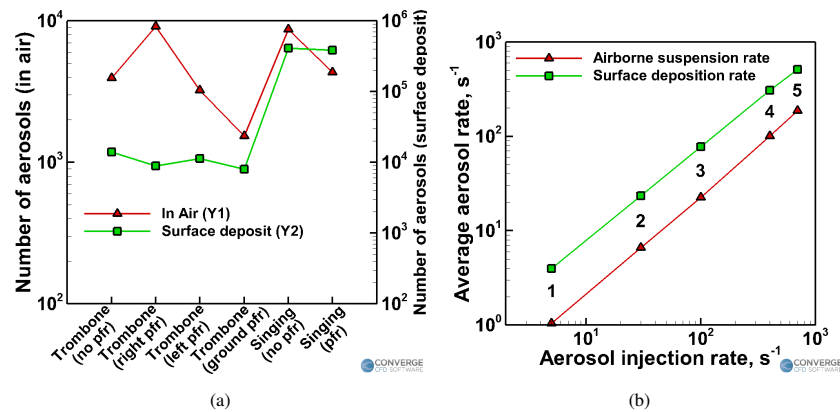


Figure 28: Summarizing the trends observed for the (a) effect of an air purifier, and (b) effect of the injection rate.

benefit, and not a negative effect. This region of benefit is usually the area right in front of the injector (i.e., the infected person, assumed to be the student here), and the vicinity around the injector. It would be advisable to place the purifier in the front of the injector in any domain. The elevation of the purifier is advised to be kept closer to the ground rather than at an elevation (in this particular case), since the aerosols don't ballistically travel forward at the same elevation of the injector (like large droplets). These aerosols follow the air streamlines and depending on those streamlines, an optimal height can be ascertained. Placing the purifier farther away from the injector reduces the effectiveness of the purifier, and in some cases worsens the situation. Thus, placing a purifier near the person whom you want to protect (in this case, the teacher) is not advisable. The streamlines from the purifier might pull aerosols which are far away from the teacher towards the purifier (and hence towards the teacher), which could be dangerous. Interestingly, the number of deposited aerosols is more or less unaffected by the presence of purifiers, as seen from both the wind instrument and the singing case (Fig. 28a). This is because a large portion of the aerosols are still deposition dominated; the aerosols get deposited at the various surfaces (such as the underside of the pianos, the vent strip, the left side window, left side wall etc.) since the solid objects/surfaces are located in spots where they directly obstruct the aerosol flow paths. Hence, these surfaces are still going to experience similar levels of deposition even if the flow patterns change. The recirculation zones starting from underneath the piano and moving upwards towards the ceiling on the back side of the piano also remain consistent among all the cases, which makes the deposition in these regions consistent to some extent. The deposition also seems to be happening rapidly compared to the suction/venting/removal of the aerosols. Hence, while the deposition more or less occurs at a similar rate, the removal vastly differs because it suctions from the airborne aerosols, causing them to travel the streamlines into the purifier.

According to Fig. 28b, the injection rate is observed to vary linearly with both the average rate of aerosols being suspended in the air as well as the average rate of aerosols being deposited in the domain. The average rate here is defined as the total number of aerosols present in air/deposited onto surfaces (see Table 3) divided by the total injection time (10 minutes in this study).

$$\dot{N}_{avg} = \frac{N_{tot}}{t_{inj}} \quad (11)$$

where \dot{N}_{avg} , N_{avg} and t_{inj} refer to the average aerosol rate, total number of aerosols and time of injection respectively. The linear correlation between the injection rate and the average aerosol rate is shown below:

$$\dot{N}_{air} \approx 0.2622\dot{N}_{inj} \quad (12)$$

$$\dot{N}_{dep} \approx 0.7436\dot{N}_{inj} \quad (13)$$

where \dot{N}_{inj} , \dot{N}_{air} and \dot{N}_{dep} refer to the number of aerosols injected per second, average airborne aerosols suspension rate and the average aerosol deposition rate, respectively.

Table 3: The total number of aerosols remaining in the domain (after 10 minutes of injection).

CASE	Type of injection mode	Aerosol injection rate (s^{-1})	Number of aerosols (in air)	Number of aerosols (surface deposit)
1	Playing a piano	5	623	2,377
2	Playing a trumpet	30	3,951	14,049
3	Playing a trombone	100	13,581	46,416
4	Singing with a mask	400	60,337	185,561
5	Singing without a mask	700	111,943	307,957

The above observations suggest that a linear trend can be expected between the injection rate and the number of airborne/deposited aerosols in a domain within a given time frame.

4. Conclusion

In this study, the effects of portable purifiers and aerosol injection rates were analyzed for different settings typically observed in a music classroom. The three categories of cases (chosen based on the typical classroom scenarios in a music school) were (a) a student playing a wind instrument in the presence of a teacher (with and without a purifier), (b) a student singing alone (with and without a purifier/mask), and (c) a student playing the piano (wearing a mask) in the presence of a teacher. Although these cases were chosen in interest of the University of Minnesota School of Music, the result analysis and observations made here could be useful for general aerosol injection scenarios. The cases here effectively vary the aerosol injection rates and/or airflow streamlines, which are not specific to a musical setting.

The effect of purifiers was found to offer significant benefits, provided the purifiers were placed in proper locations, offering orders of magnitude higher rates of aerosol removal compared to cases having no purifiers (where the removal might even be close to zero). Placing the purifiers close to the injector, and specifically in the path of aerosol injection/transport could offer positive benefits. The purifier should also preferably be kept in a position where the exhaust flow aids in the natural recirculation of the room. This can be found in the purifier on the ground case where the exhaust airflow from the purifier travels underneath the piano and follows the natural recirculation

zone above. Placing the purifier in a location where the exhaust flow significantly changes the airflow streamlines in the domain (e.g., purifier on the left or right side at an elevation, where the exhaust airflow causes significant airflow streamline changes and mixing in the domain) may cause more spreading of the aerosols (although some reduction in total airborne aerosols may be achieved, as found in the left table purifier case). The study therefore advises that the purifier be kept close to the injector, and away from the individuals whom you want to protect. This could apply even to a case with multiple purifiers.

Using purifiers could help in achieving ventilation rates as suggested by WHO and CDC guidelines, since the in-built HVAC ventilation rates of the building may not be sufficient to achieve the desired aerosol removal rates. It was observed that using a purifier also aids in improving the natural ventilation (through the building vents), which further helps in achieving removal times within the CDC prescribed values. This fact helps in arriving at an effective break period of 25 minutes between class sessions, where the airborne aerosol removal using a purifier is almost 97%. Since the number of airborne aerosols fluctuate about a mean value after an initial transient period, the break period will apply to any classroom duration.

Finally, an almost linear correlation between the injection rate and the number of aerosols remaining in the air and deposited onto surfaces was observed. This detail could predict similar quantities when a different injection rate is used, without the need for simulating the entire domain again.

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